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The
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Department of Electrical Engineering

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Infinite Systems of Linear
Equations in an Infinite
Number of Unknowns

Contract W 36-039 sc33634

Department of the Army Project: 3-99-05-022

Signal Corps Project: 122B-0

EVANS SIGNAL LABORATORY, BELMAR, NEW JERSEY

302-42

12 May 1951



The Ohio State University
Research Foundation
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REPORT

by

THE OHIO STATE UNIVERSITY RESEARCH FOUNDATION

COLUMBUS 10, OHIO

Cooperator Evans Signal Laboratory
 Belmar, New Jersey
 Department of the Army Project: 3-99-05-022
 Signal Corps Project: 122B-0

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Investigation of Determination of Echoing Area
 Characteristics of Various Objects

Subject of Report Infinite Systems of Linear Equations
 in an Infinite Number of Unknowns

Submitted by Antenna Laboratory
 Department of Electrical Engineering

Date 12 May 1951

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INFINITE SYSTEMS OF LINEAR EQUATIONS
IN AN INFINITE NUMBER OF UNKNOWN

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OHIO STATE UNIVERSITY RESEARCH FOUNDATION, ANTENNA LAB.,
COLUMBUS (PROJECT REPORT 302-42)

DETERMINATION OF ECHOING AREA CHARACTERISTICS OF VARIOUS
OBJECTS - INFINITE SYSTEMS OF LINEAR EQUATIONS IN AN
INFINITE NUMBER OF UNKNOWN - AND APPENDICES I-III

FADELL, EDWARD R.; ADNEY, J.E., JR.; KENNAUGH, EDWARD M.
AND OTHERS 12 MAY '51 41PP

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INFINITE SYSTEMS OF LINEAR EQUATIONS
IN AN INFINITE NUMBER OF UNKNOWN'S

A. INTRODUCTION

The solution of a large class of physical problems, including diffraction of electromagnetic waves by periodic structures, or combinations of simple scatterers, and resonance phenomena in enclosed spaces, lead to infinite systems of linear equations in an infinite number of unknowns. Conventional methods of solving finite sets of linear equations must be extended with care to the infinite system. This report is a brief summary of available information on the solution of such infinite systems, with emphasis on the important distinctions between the finite and infinite cases.

B. EXTENSION OF CRAMER'S RULE TO INFINITE SYSTEMS

CRAMER'S RULE

Consider the set of equations:

$$\sum_{k=1}^n a_{ik} x_k = b_i \quad (i = 1, 2, 3, \dots, n). \quad (1)$$

Let the determinant of the array a_{ik} be denoted by Δ_n , where

$$\Delta_n = \begin{vmatrix} a_{11} & a_{12} & a_{13} & \cdots & \cdots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \cdots & \cdots & a_{2n} \\ a_{31} & a_{32} & a_{33} & \cdots & \cdots & a_{3n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & a_{n3} & \cdots & \cdots & a_{nn} \end{vmatrix} \quad (2)$$

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and let $\Delta_n^{(k)}$ represent the determinant of the array formed by replacing the k^{th} column of (2) by the set b_1, b_2, \dots, b_n . If the determinant Δ_n is nonzero, Cramer's rule states that the unknowns x_k are given by

$$x_k = \frac{\Delta_n^{(k)}}{\Delta_n} \quad (3)$$

This is the unique solution to system (1) if Δ_n is nonzero; if Δ_n is zero, the system of equations may possess up to n independent solutions or no solution depending upon the values of b_i , and a modified approach must be used.

For an infinite system of equations the concept of determinant is open to definition,¹ but an extension of Cramer's rule to such a system is suggested. Consider the infinite system

$$\sum_{k=1}^{\infty} a_{ik} x_k = b_i \quad (i = 1, 2, 3, \dots) \quad (4)$$

If this infinite array is considered as the limit of a sequence of finite square arrays, the n^{th} array in the sequence being given by (1), then logical extension of Cramer's rule as applied to finite systems would suggest that the solution be given by the limit (when it exists):

$$x_k = \lim_{n \rightarrow \infty} \frac{\Delta_n^{(k)}}{\Delta_n} \quad (5)$$

Such an extension of Cramer's rule is not generally valid, as several examples will show. Consider the infinite system of equations:

$$\sum_{j=1}^{\infty} a_{ij} x_j = b_i \quad (i = 1, 2, 3, \dots) \quad (6)$$

$$a_{ij} = 0 \quad i < j$$

$$a_{ij} = 1 \quad i \geq j$$

$$b_i = (-1)^i$$

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By inspection it is seen that

$$\begin{aligned}\Delta_n &= 1 \quad \text{for all } n, \\ \Delta_n^{(k)} &= 2(-1)^k, \text{ where } k \neq n, \text{ and} \\ \Delta_n^{(n)} &= (-1)^n.\end{aligned}$$

Therefore, by (5),

$$x_k = \lim_{n \rightarrow \infty} \frac{\Delta_n^{(k)}}{\Delta_n} = 2(-1)^k. \quad (7)$$

Upon substitution of the "solution" into the equations of (6), however, the row series do not converge. The extension of Cramer's rule does not yield a verifiable solution in this case. Another system for which the extension of Cramer's rule is in doubt is given by

$$\sum_{j=1}^{\infty} a_{ij} x_j = b_i \quad (i = 1, 2, 3, \dots), \quad (8)$$

where $a_{ij} = 0$, except $a_{i,i} = 1$, $a_{i,i+1} = -1$, and $b_i = 0$.

By inspection

$$\begin{aligned}\Delta_n &= 1, \\ \Delta_n^{(k)} &= 0.\end{aligned}$$

Therefore, by (5),

$$x_k = \lim_{n \rightarrow \infty} \frac{\Delta_n^{(k)}}{\Delta_n} = 0. \quad (9)$$

By inspection, however, an infinite number of solutions to system (8) exist of the form $x_k = c$. In this instance the extension of Cramer's rule gives a verifiable solution, but it is not a unique solution.

As the preceding examples illustrate, application of the extended form of Cramer's rule to infinite systems must be made with care.

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Appendix I develops sufficient conditions for the application of Cramer's rule to infinite systems of equations. It must be emphasized that these conditions need not be satisfied for Cramer's rule to apply; they are sufficient but not necessary conditions. Two types of conditions will be noted. The first set of conditions are those sufficient for the infinite set of linear equations to have a unique solution given by the extended Cramer's rule. They are:

1. The determinant of the array must be "normal"
2. The limit of the Δ_n must be nonzero
3. The sequence b_i must be bounded.

The determinant of an array is said to be "normal" if the double series $\sum_i \sum_j (a_{ij} - \delta_{ij})$ converges absolutely, where δ_{ij} denotes the Kronecker delta. The second set of conditions are less stringent, and are sufficient for the infinite set of equations to possess a solution (not necessarily unique) given by the extended form of Cramer's rule. These are:

1. The ratio $\frac{\Delta_n^{(k)}}{\Delta_n}$ converges, uniformly with k , to a limit $\frac{\Delta^{(k)}}{\Delta}$ for $k = 1, 2, 3, \dots$
2. $\Delta_n \neq 0$, for n sufficiently large
3. $\sum_{j=1}^{\infty} |a_{ij}|$ converges for $i = 1, 2, \dots$
4. The sequence b_i must be bounded.

The second set of conditions essentially substitutes the weaker condition of absolute summability of the rows for the stronger condition that the determinant of the array be normal. In many cases arising from analysis of physical problems the existence of a unique solution may be implied by other considerations, and the weaker set of conditions used to justify extension of Cramer's rule to the system. Note that (8) is an example of a system satisfying the weaker set of conditions for the application of Cramer's rule, and the solution given by this rule is valid, but not unique. Since the system does not satisfy the stronger conditions (its determinant is not normal) one would not expect this solution to be unique.

The extension of Cramer's rule to infinite systems of equations is not a satisfactory general method of solution, therefore, since

1. It does not yield the general solution
2. Necessary and sufficient conditions for application of this rule are not known
3. Sufficient conditions which may be stipulated are difficult to test in an actual system, since the absolute convergence of a double series must be ascertained.

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It must be emphasized that for special systems of equations, where the sufficient conditions for application of Cramer's rule are obviously satisfied, this rule gives a rapid method of obtaining a solution, and is quite useful.

C. THE METHOD OF SCHMIDT

The most satisfactory general technique for solving infinite systems of linear equations has been developed by E. Schmidt. The text of an excellent paper² on this method by Maxime Bocher and Louis Brand is reproduced in full in Appendix II. In brief, the important characteristics of Schmidt's method are as follows:

1. The matrix of the infinite system of equations is multiplied by its complex conjugate transpose to form a new array
2. The solution of the system is given by the limit of the ratios of determinants, formed from subarrays of increasing order, much as in Cramer's method
3. If a unique solution of finite norm exists, this method yields it; if more than one solution exists, this method gives the one of minimum norm and can be used to obtain the general solution
4. Necessary and sufficient conditions for the existence of a solution of finite norm are given.

It may be noted that the solutions of physical problems which are of interest are those of minimum norm, exactly those given by Schmidt's method.

D. CONCEPT OF INVERSE APPLIED TO INFINITE SYSTEMS

The infinite system of linear eqs. (4) may be written in matrix form as

$$AX = B,$$

where A is the infinite matrix of coefficients a_{ij} , X is a column vector in the unknowns x_j , and B is the column vector of constants b_i . In analogy with a finite system, it may be asked if A has an inverse matrix C such that

$$AC = CA = I.$$

Then the solution would be given by:

$$X = CB$$

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Infinite matrices, however, do not generally possess unique inverses. An infinite matrix may possess an infinite number of right or left inverses. If an infinite matrix possesses both a right and left inverse they are equal and unique. To illustrate a matrix which possesses an infinite number of right inverses, consider the infinite array $A = ((a_{ij}))$ where $a_{ij} = 0$, except $a_{i, i+1} = 1$. By inspection, the matrix $C = ((c_{ij}))$, where c_{1j} is arbitrary, $c_{i+1, i} = 1$, and all other c_{ij} are zero, is a right inverse of A . That is

$$AC = I$$

for an infinite number of matrices C differing by elements in the first row. No left inverse exists for A , however, since the product CA has all zeros in its first column for any matrix C .

Appendix III outlines a modification of Schmidt's method which develops sufficient conditions for a matrix B to exist such that, if

$$AX = C,$$

the solution vector is given by

$$X = BC,$$

where A and B are infinite square matrices, and X and C are infinite column vectors.

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E. APPENDICES I TO III

APPENDIX I

1. NORMAL ARRAYS

Consider the following infinite square array:

$$\begin{vmatrix}
 1+a_{11} & a_{12} & a_{13} & a_{14} & \cdots & \cdots & \cdots \\
 a_{21} & 1+a_{22} & a_{23} & a_{24} & \cdots & \cdots & \cdots \\
 a_{31} & a_{32} & 1+a_{33} & a_{34} & \cdots & \cdots & \cdots \\
 a_{41} & a_{42} & a_{43} & 1+a_{44} & \cdots & \cdots & \cdots \\
 \vdots & \vdots & \vdots & \vdots & \ddots & \ddots & \ddots \\
 \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \ddots
 \end{vmatrix} \quad (1)$$

where the a_{ij} are complex quantities, and the double series $\sum_{i=1}^{\infty} \sum_{j=1}^{\infty} |a_{ij}|$ converges. Such an array is described as "normal". Furthermore, let $A_j = \sum_{i=1}^{\infty} |a_{ij}|$, where the series defining A_j converges since the double series $\sum_{i=1}^{\infty} \sum_{j=1}^{\infty} |a_{ij}|$ converges. $\sum_{j=1}^{\infty} A_j$ converges for the same reason. It then follows that the sequence of products $\prod_n = \prod_{j=1}^n (1+A_j)$ converges to a limit Π . Consider now the determinants of the finite square subarrays

$$\Delta_n = \begin{vmatrix}
 1+a_{11} & a_{12} & \cdots & \cdots & \cdots & a_{1n} \\
 a_{21} & 1+a_{22} & \cdots & \cdots & \cdots & a_{2n} \\
 \vdots & \vdots & \ddots & \ddots & \ddots & \vdots \\
 \vdots & \vdots & \vdots & \ddots & \ddots & \vdots \\
 a_{n1} & a_{n2} & \cdots & \cdots & \cdots & 1+a_{nn}
 \end{vmatrix} \quad (2)$$

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These determinants are sums of certain products of the a_{ij} , with proper sign attached. The same products occur also, in absolute value, in the development of Π_n . Furthermore, Δ_{n+p} contains all the terms of Δ_n , and the other terms of Δ_{n+p} appear, in absolute value, in $\Pi_{n+p} - \Pi_n$. Therefore, it follows that $|\Delta_n| \leq \Pi_n$, $|\Delta_{n+p} - \Delta_n| \leq \Pi_{n+p} - \Pi_n$, and

$$\lim_{n \rightarrow \infty} \Delta_n = \Delta \quad (3)$$

exists, where $|\Delta| \leq \Pi$. A normal array may be said to possess an infinite determinant Δ considered as a limit of determinants of finite square subarrays, and this limit determinant is bounded by Π .

The determinant Δ_i^k of an array formed by replacing the k^{th} column of a normal array with a bounded sequence also exists, and $\Delta_i^k \leq M\Pi$, where M is the upper bound to the sequence.

2. LAPLACE'S DEVELOPMENT OF NORMAL ARRAYS

The analogue of Laplace's development of a finite determinant for an infinite system will now be established. A preliminary definition is required.

DEFINITION: By the minor (k) of the determinant Δ of a normal matrix (array) A , we shall mean the resulting determinant Δ^k of the matrix formed by substituting, for the k^{th} column of A the sequence $b_j = \delta_{ij}$. As in the finite case, the minor (k) does not change if all the elements in the i^{th} row are replaced by zeros except the element in the k^{th} column.

THEOREM 1: If A is a normal matrix, and c_i is a bounded sequence, then

- (a) $\sum_{i=1}^{\infty} |(k)|^i$ converges, and its value does not exceed Π
- (b) $\Delta^k = \sum_{i=1}^{\infty} (k)^i c_i$, and the series on the right converges absolutely.

PROOF: Since the convergence of $\sum_{i=1}^{\infty} |(k)|^i$ implies the convergence of $\sum_{i=1}^{\infty} (k)^i c_i$, we first show that $\sum_{i=1}^{\infty} |(k)|^i$ converges. It suffices to show that the partial sums $\sum_{i=1}^n |(k)|^i$ are bounded for all n .

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Let Δ^k be the infinite determinant of the matrix formed by substituting for the k^{th} column of A the sequence b_i where

$$b_i = \frac{\binom{i}{k}}{\binom{i}{k}} , i \leq n \quad (4)$$

$$b_i = 0 , i > n . \quad (5)$$

Here the b_i are bounded by unity, and n is arbitrary. Then $\Delta^k = \sum_{i=1}^n \binom{i}{k}$ and $|\Delta^k| \leq \Pi$. Since n is arbitrary, this implies the convergence of

$$\sum_{i=1}^{\infty} \binom{i}{k}$$

It remains to verify the second part of Theorem 1. Let n be an arbitrary integer, and form from the bounded sequence c_i the sequences α_i and β_i , where

$$\alpha_i = c_i , i < n+1 \quad (6)$$

$$\alpha_i = 0 , i \geq n+1 , \quad (7)$$

and

$$\beta_i = 0 , i \leq n \quad (8)$$

$$\beta_i = c_i , i > n . \quad (9)$$

Let Δ^k be the infinite determinant of the matrix formed from A by replacing the k^{th} column by the given sequence c_i . Let Δ_1^k be the infinite determinant of the matrix formed from A by replacing the k^{th} column by the sequence α_i . Let Δ_2^k be the infinite determinant of the matrix formed from A by replacing the k^{th} column by the sequence β_i . Then

$$\Delta_1^k = \sum_{i=1}^n \binom{i}{k} c_i = S_n , \quad (10)$$

$$\Delta^k - S_n = \Delta_2^k \quad (11)$$

If Δ_{2n}^k represents the finite determinant obtained from the first n^2 elements of the

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matrix yielding Δ_2^k , $\Delta_{2n}^k = 0$ if $n \leq k$, since the corresponding matrix would contain an entire column of zeros. Furthermore,

$$|\Delta_2^k - \Delta_{2n}^k| \leq M (\Pi - \Pi_n), \quad (12)$$

where M is an upper bound to the c_i . Therefore, for $n \geq k$,

$$|\Delta_2^k - \Delta_{2n}^k| = |\Delta_2^k| = |\Delta^k - S_n| \leq C (\Pi - \Pi_n), \quad (13)$$

and in the limit

$$S_n \rightarrow \Delta_k, \quad (14)$$

establishing the second part of theorem. If the elements of A are $a_{ij} + \delta_{ij}$ the following statements are evident:

$$(k) + \sum_{i=1}^{\infty} a_{ij} (k) = \delta_{jk} \Delta, \quad (15)$$

$$(j) + \sum_{k=1}^{\infty} a_{jk} (k) = \delta_{ij} \Delta, \quad (16)$$

and the double series $\sum_{i=1}^{\infty} \sum_{k=1}^{\infty} a_{jk} c_i (k)$ is absolutely convergent. We now apply these properties of normal arrays to solutions of infinite systems of linear equations.

3. EXTENSION OF CRAMER'S RULE TO INFINITE SYSTEMS

THEOREM 2: Given the infinite system of linear equations

$$\sum_{j=1}^{\infty} (\delta_{ij} + a_{ij}) x_j = c_i, \quad i = 1, 2, 3, \dots, \quad (17)$$

where $\delta_{ij} + a_{ij}$ is a normal array, $|c_i| < M < \infty$

for all i , and the infinite determinant Δ of the array is nonzero. It then follows that the unique solution of the equations is given by

$$x_k = \frac{\Delta^k}{\Delta}, \quad (18)$$

where Δ^k is the determinant of the array formed from the given array by substituting

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the sequence c_i for the k^{th} column.

PROOF:

(a). For an arbitrary j

$$\Delta^j + \sum_{k=1}^{\infty} a_{jk} \Delta^k = \sum_{i=1}^{\infty} c_i (j) + \sum_{k=1}^{\infty} a_{jk} \sum_{i=1}^{\infty} c_i (i) \quad (19)$$

$$= \sum_{i=1}^{\infty} c_i \left[(j) + \sum_{k=1}^{\infty} a_{jk} (i) \right] \quad (20)$$

$$= c_j \Delta. \quad (21)$$

Since Δ is nonzero,

$$\frac{\Delta^j}{\Delta} + \sum_{k=1}^{\infty} a_{jk} \frac{\Delta^k}{\Delta} = c_j, \quad (22)$$

meaning that

$$x_k = \frac{\Delta^k}{\Delta}$$

yields the components of a solution.

(b). Proof of uniqueness.

Suppose that eqs. (17) permitted another solution vector $(y_1, y_2, \dots, y_{k_2}, \dots)$, where for some j_0

$$x_{j_0} - y_{j_0} \neq 0. \quad (22)$$

Then the homogeneous system

$$\sum_{j=1}^{\infty} (\delta_{ij} + a_{ij}) z_j = 0, \quad i = 1, 2, 3, \dots \quad (23)$$

admits of a nonzero solution $z_k = x_k - y_k$ where $z_{j_0} = x_{j_0} - y_{j_0} \neq 0$. However, for an arbitrary j , we have

$$\sum_{i=1}^{\infty} (j) \left(z_i + \sum_{k=1}^{\infty} a_{ik} z_k \right) = 0. \quad (24)$$

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$$\sum_{k=1}^{\infty} z_k \left[\binom{k}{j} + \sum_{i=1}^{\infty} a_{ik} \binom{i}{j} \right] = z_j \Delta \equiv 0, \quad (25)$$

and since $\Delta \neq 0$, $z_j = 0$ for every j . Since this contradicts (22), the uniqueness of solution is proven. When $\Delta = 0$, Theorem 2 does not apply, and we refer the reader to Riesz, *Les Systems d'Equations Lineaires*.³

In general Theorem 2 is difficult to apply, since the hypotheses are stringent, and even the investigation of the convergence of the double series $\sum_i \sum_j |a_{ij}|$ offers great difficulty. The following theorem might also prove useful as an extension of Cramer's rule.

THEOREM 3: Given the infinite system of equations

$$\sum_{j=1}^{\infty} a_{ij} x_j = c_i, \quad i = 1, 2, 3, \dots, \quad (23)$$

where $\sum_{j=1}^{\infty} |a_{ij}|$ converges for $i = 1, 2, 3, \dots$, and Δ_n is nonzero for n sufficiently large. Then, if the ratio $\frac{\Delta_n^k}{\Delta_n}$ converges uniformly with k to a limit $\frac{\Delta^k}{\Delta}$ for $k = 1, 2, 3, \dots$, a solution is given by

$$x_k = \frac{\Delta^k}{\Delta}. \quad (24)$$

PROOF: Let i be fixed but completely arbitrary. Assert

$$\sum_{j=1}^{\infty} a_{ij} \frac{\Delta^j}{\Delta} = c_i. \quad (25)$$

It suffices to show that for n large enough,

$$\left| \sum_{j=1}^n a_{ij} \frac{\Delta^j}{\Delta} - c_i \right| < \epsilon, \quad (26)$$

where ϵ is an arbitrary positive quantity. For $n \geq i$

$$\sum_{j=1}^n a_{ij} \frac{\Delta_n^j}{\Delta_n} = c_i, \quad (27)$$

and

$$\left| \sum_{j=1}^n a_{ij} \frac{\Delta^j}{\Delta} - c_i \right| \leq \left| \sum_{j=1}^n a_{ij} \frac{\Delta^j}{\Delta} - \sum_{j=1}^n a_{ij} \frac{\Delta_n^j}{\Delta_n} \right| + \left| \sum_{j=1}^n a_{ij} \frac{\Delta_n^j}{\Delta_n} - c_i \right|. \quad (28)$$

APPENDIX II

ON LINEAR EQUATIONS WITH AN INFINITE NUMBER OF VARIABLES.

BY MAXIME BÖCHER AND LOUIS BRAND.

E. Schmidt's treatment of a system of linear equations with an infinite number of variables* is of such essential simplicity and importance that it seems destined to become classical. The original memoir, however, owing to its condensation and to the rather abstract form which it has in parts is not entirely easy reading for the beginner, and Kowalewski's presentation,† while attractive in some respects, is extremely long and so arranged that unless one reads the whole it is almost impossible to get at the essential results.

The following treatment, which so far as it goes is complete in itself, is a modification of those heretofore given. Its characteristic features are, on the one hand, that it avoids altogether the process of normalization which plays such an essential and often repeated rôle in the earlier treatments; and, on the other hand, that it deals first with the case of a finite number of equations involving an infinite number of variables and regards the case of an infinite number of equations as a limit.

For the sake of clearness, though this is not logically necessary, the algebraic case of a finite number of variables is taken up first.

1. **Complex Quantities with k Components.** The real and complex quantities of ordinary algebra shall be termed *scalars* in distinction to the higher complex quantities, (a_1, a_2, \dots, a_k) , which are aggregates of k scalars—the *components* of the complex quantity—taken in a definite order. Such complex quantities will be denoted by Greek letters. That complex quantity whose components are all zero shall be denoted by 0. Two complex quantities,

$$\alpha = (a_1, a_2, \dots, a_k), \quad \beta = (b_1, b_2, \dots, b_k),$$

are said to be equal when and only when $a_i = b_i$ ($i = 1, 2, \dots, k$). We define the sum of α and β by

$$\alpha + \beta = (a_1 + b_1, a_2 + b_2, \dots, a_k + b_k);$$

and the product of α by a scalar, p , by

$$p\alpha = \alpha p = (pa_1, pa_2, \dots, pa_k).$$

* *Rendiconti del Circolo Matematico di Palermo*, vol. 25 (1908), pp. 56-77.

† *Einführung in die Determinantentheorie* (Veit: Leipzig, 1909), pp. 407-455.

We may regard the coefficients of each of these equations as the components of a complex quantity:

$$\alpha_i = (a_{i1}, a_{i2}, \dots, a_{in}) \quad (i = 1, 2, \dots, n),$$

and also the x 's as the components of the complex quantity

$$\xi = (x_1, x_2, \dots, x_n).$$

Our system of equations may then be written

$$(1) \quad \alpha_1 \xi = 0, \alpha_2 \xi = 0, \dots, \alpha_n \xi = 0.$$

THEOREM 1. *If ξ satisfies equations (1) and is linearly dependent upon $\bar{\alpha}_1, \bar{\alpha}_2, \dots, \bar{\alpha}_n$, then $\xi = 0$.*

For suppose that

$$\xi = c_1 \bar{\alpha}_1 + c_2 \bar{\alpha}_2 + \dots + c_n \bar{\alpha}_n.$$

Then multiplying equations (1) by $\bar{c}_1, \bar{c}_2, \dots, \bar{c}_n$ respectively and adding we get

$$(\bar{c}_1 \alpha_1 + \bar{c}_2 \alpha_2 + \dots + \bar{c}_n \alpha_n) \xi = \bar{\xi} \xi = 0.$$

Hence $\xi = 0$, as was to be proved.

COROLLARY. *If ξ satisfies the equations*

$$\bar{\alpha}_1 \xi = 0, \bar{\alpha}_2 \xi = 0, \dots, \bar{\alpha}_n \xi = 0$$

and is linearly dependent upon $\alpha_1, \alpha_2, \dots, \alpha_n$, then $\xi = 0$.

We are now in position to obtain a criterion for the linear dependence of n complex quantities. If $\alpha_1, \alpha_2, \dots, \alpha_n$ are linearly dependent,

$$c_1 \alpha_1 + c_2 \alpha_2 + \dots + c_n \alpha_n = 0,$$

where not all the c 's are zero. Multiplying this relation in succession by $\bar{\alpha}_1, \bar{\alpha}_2, \dots, \bar{\alpha}_n$, we obtain the n equations

$$c_1 \alpha_1 \bar{\alpha}_i + c_2 \alpha_2 \bar{\alpha}_i + \dots + c_n \alpha_n \bar{\alpha}_i = 0 \quad (i = 1, 2, \dots, n).$$

In this system of homogeneous, linear equations in c_1, c_2, \dots, c_n the c 's are not all zero and hence the determinant of the system must vanish. We call this determinant, which it should be noticed is a *real* scalar, the *Gramian* of $\alpha_1, \alpha_2, \dots, \alpha_n$ and denote it by $G(\alpha_1, \alpha_2, \dots, \alpha_n)$. Thus

$$(2) \quad G(\alpha_1, \alpha_2, \dots, \alpha_n) = \begin{vmatrix} \alpha_1 \bar{\alpha}_1 & \alpha_1 \bar{\alpha}_2 & \dots & \alpha_1 \bar{\alpha}_n \\ \alpha_2 \bar{\alpha}_1 & \alpha_2 \bar{\alpha}_2 & \dots & \alpha_2 \bar{\alpha}_n \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_n \bar{\alpha}_1 & \alpha_n \bar{\alpha}_2 & \dots & \alpha_n \bar{\alpha}_n \end{vmatrix}.$$

The relation $G = 0$ is therefore a necessary condition for linear dependence:

THEOREM 3. *If the equations*

$$\alpha_1 \xi = 0, \alpha_2 \xi = 0, \dots, \alpha_n \xi = 0,$$

are linearly independent, their general solution is given by (5), where η is an arbitrary complex quantity.

When ξ_1 vanishes, we see from (3) that $\bar{\eta}$ is linearly dependent upon $\bar{\alpha}_1, \bar{\alpha}_2, \dots, \bar{\alpha}_n$. Conversely, if $\bar{\eta}$ is linearly dependent upon $\bar{\alpha}_1, \bar{\alpha}_2, \dots, \bar{\alpha}_n$, the same is true of ξ_1 , and hence, by Theorem 1, $\xi_1 = 0$. Now to two $\bar{\eta}$'s correspond two ξ_1 's whose difference is precisely that solution of (1) which corresponds to the difference between the $\bar{\eta}$'s. Consequently two different $\bar{\eta}$'s yield the same ξ_1 when and only when their difference is linearly dependent upon $\bar{\alpha}_1, \bar{\alpha}_2, \dots, \bar{\alpha}_n$.

If $n > k$ the equations (1) are necessarily linearly dependent, so that Theorem 3 does not apply to this case. If $n = k$ every $\bar{\eta}$ is linearly dependent on the $\bar{\alpha}$'s, so that in this case, as is well known, equations (1) have only the trivial solution zero. If $n < k$ we can find $k - n$ complex quantities $\bar{\alpha}_{n+1}, \bar{\alpha}_{n+2}, \dots, \bar{\alpha}_k$ such that $\bar{\alpha}_1, \bar{\alpha}_2, \dots, \bar{\alpha}_k$ are linearly independent. Then every η may be written as $C_1 \bar{\alpha}_1 + C_2 \bar{\alpha}_2 + \dots + C_k \bar{\alpha}_k$; but as a change in $\bar{\eta}$ by a quantity linearly dependent upon $\bar{\alpha}_1, \bar{\alpha}_2, \dots, \bar{\alpha}_n$ does not affect formula (5), we lose nothing in generality if we assume $\bar{\eta}$ of the form

$$\bar{\eta} = C_{n+1} \bar{\alpha}_{n+1} + \dots + C_k \bar{\alpha}_k.$$

Thus the solution (5) contains, as it should, $k - n$ arbitrary scalars, C_{n+1}, \dots, C_k , and contains them linearly and homogeneously.

A formula for the norm of ξ_1 is readily found. From (3):

$$(6) \quad \text{norm } \xi_1 = \bar{c}_1 \alpha_1 \xi_1 + \dots + \bar{c}_n \alpha_n \xi_1 + \eta \xi_1 = \eta \xi_1.$$

If we form the product $\eta \xi_1$ from (5) by multiplying the last row of the determinant in the numerator by η , it is clear that

$$(7) \quad \text{norm } \xi_1 = \frac{G(\alpha_1, \alpha_2, \dots, \alpha_n, \eta)}{G(\alpha_1, \alpha_2, \dots, \alpha_n)}.$$

We proceed to use this relation to establish an important property of Gramians. In (7) $\alpha_1, \alpha_2, \dots, \alpha_n, \eta$ may be regarded as $n+1$ arbitrary complex quantities; we will assume that they are linearly independent. Then $\bar{\eta}$ is clearly not a linear combination of $\bar{\alpha}_1, \bar{\alpha}_2, \dots, \bar{\alpha}_n$, so that $\xi_1 \neq 0$ and $\text{norm } \xi_1 > 0$. Moreover this assumption entails that none of $\alpha_1, \alpha_2, \dots, \alpha_n, \eta$ vanish, and hence the Gramian of any one, e. g., $G(\alpha_1) = \alpha_1 \bar{\alpha}_1$, is real and positive. Hence by giving to n in (7) in succession the values 1, 2, \dots , we establish by mathematical induction

THEOREM 4. *The Gramian of any number of linearly independent complex quantities is real and positive.*

3. **Non-Homogeneous Linear Algebraic Equations.** We come now to the system of non-homogeneous equations :

$$(8) \quad \alpha_1 \xi = b_1, \alpha_2 \xi = b_2, \dots, \alpha_n \xi = b_n,$$

where we again assume that $\alpha_1, \alpha_2, \dots, \alpha_n$ are linearly independent, and try to find a solution of the form

$$(9) \quad \xi_0 = c_1 \bar{\alpha}_1 + c_2 \bar{\alpha}_2 + \dots + c_n \bar{\alpha}_n.$$

Substituting this in (8), we obtain n linear equations, which may be obtained from equations (4) by replacing their right hand members by b_1, b_2, \dots, b_n respectively. These can, as above, be solved for the c 's by Cramer's rule, and the results substituted in (9). This gives

$$(10) \quad \xi_0 = \frac{\begin{vmatrix} \alpha_1 \bar{\alpha}_1 & \alpha_1 \bar{\alpha}_2 & \dots & \alpha_1 \bar{\alpha}_n & -b_1 \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \alpha_n \bar{\alpha}_1 & \alpha_n \bar{\alpha}_2 & \dots & \alpha_n \bar{\alpha}_n & -b_n \\ \bar{\alpha}_1 & \bar{\alpha}_2 & \dots & \bar{\alpha}_n & 0 \end{vmatrix}}{G(\alpha_1, \alpha_2, \dots, \alpha_n)}.$$

That this is really a solution of (8) we see by direct substitution. For if we form the product $\alpha_i \xi_0$, the last row of the determinant in the numerator becomes

$$\alpha_i \bar{\alpha}_1, \alpha_i \bar{\alpha}_2, \dots, \alpha_i \bar{\alpha}_n, 0;$$

and, when the i th row is subtracted from this, it appears that

$$\alpha_i \xi_0 = b_i G_i G = b_i.$$

We have thus proved

THEOREM 5. *If $\alpha_1, \alpha_2, \dots, \alpha_n$ are linearly independent, the equations (8) have one and only one solution of the form (9), and this is given by (10).*

The general solution of (8) is of course obtained by adding to the particular solution (10) the general solution (5) of the homogeneous equations (1); it is therefore

$$(11) \quad \xi = \xi_0 + \xi_1 = \frac{\begin{vmatrix} \alpha_1 \bar{\alpha}_1 & \alpha_1 \bar{\alpha}_2 & \dots & \alpha_1 \bar{\alpha}_n & \alpha_1 \bar{\eta} - b_1 \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \alpha_n \bar{\alpha}_1 & \alpha_n \bar{\alpha}_2 & \dots & \alpha_n \bar{\alpha}_n & \alpha_n \bar{\eta} - b_n \\ \bar{\alpha}_1 & \bar{\alpha}_2 & \dots & \bar{\alpha}_n & \bar{\eta} \end{vmatrix}}{G(\alpha_1, \alpha_2, \dots, \alpha_n)}.$$

The solution (10) of (8), which is characterized by being the only solution of (8) which is linearly dependent upon the $\bar{\alpha}$'s, shall be called the *principal solution* of (8). It has also another characteristic property which may

be deduced as follows. From (11) we see that

$$\xi \bar{\xi} = (\xi_0 + \xi_1)(\bar{\xi}_0 + \bar{\xi}_1) = \xi_0 \bar{\xi}_0 + \xi_0 \bar{\xi}_1 + \xi_1 \bar{\xi}_0 + \xi_1 \bar{\xi}_1;$$

and from (9)

$$\xi_0 \bar{\xi}_1 = c_1 \bar{\alpha}_1 \bar{\xi}_1 + c_2 \bar{\alpha}_2 \bar{\xi}_1 + \dots + c_n \bar{\alpha}_n \bar{\xi}_1 = 0,$$

remembering that ξ_1 is a solution of equations (1). Consequently $\xi_1 \bar{\xi}_0 = 0$, and

$$(12) \quad \text{norm } \xi = \text{norm } \xi_0 + \text{norm } \xi_1,$$

so that

$$\text{norm } \xi \geq \text{norm } \xi_0,$$

the equality sign holding only when $\xi_1 = 0$, in which case $\xi = \xi_0$. Thus we have

THEOREM 6. *Among the solutions of (8) no other has so small a norm as the principal solution.*

To obtain a formula for $\text{norm } \xi_0$ we multiply the last row of the determinant in the numerator of (10) by $\bar{\xi}_0$ and simplify by use of the equations, $\bar{\alpha}_i \bar{\xi}_0 = \bar{b}_i$; thus*

$$(13) \quad \text{norm } \xi_0 = - \frac{\begin{vmatrix} \alpha_1 \bar{\alpha}_1 & \alpha_1 \bar{\alpha}_2 & \dots & \alpha_1 \bar{\alpha}_n & b_1 \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \alpha_n \bar{\alpha}_1 & \alpha_n \bar{\alpha}_2 & \dots & \alpha_n \bar{\alpha}_n & b_n \\ \bar{b}_1 & \bar{b}_2 & \dots & \bar{b}_n & 0 \end{vmatrix}}{G(\alpha_1, \alpha_2, \dots, \alpha_n)}.$$

Norm ξ is now given by (12).

4. System of a Finite Number of Linear Equations in an Infinite Number of Variables. We now consider a system of n equations

$$(14) \quad a_{i1}x_1 + a_{i2}x_2 + \dots = 0 \quad (i = 1, 2, \dots, n),$$

where the number of unknowns x_1, x_2, \dots is infinite. For this purpose we use complex quantities with an infinite number of components. If $\alpha = (a_1, a_2, \dots)$ is such a complex quantity, we consider the series $a_1^2 + a_2^2 + \dots$. If this series is convergent, we say that the complex quantity has a finite norm and define

$$\text{norm } \alpha \equiv |a_1|^2 + |a_2|^2 + \dots, \quad |\alpha| \equiv \sqrt{\text{norm } \alpha}.$$

* If not all of the b 's vanish, it is clear from equations (8) that $\xi_0 \neq 0$, and hence $\text{norm } \xi_0 > 0$. By means of (13) we may now prove at once the following

THEOREM. *If the Gramian of linearly independent complex quantities is bordered by scalars that do not all vanish so as to form a determinant of the type of that in (13), this bordered Gramian is negative.*

The sum of $\alpha = (a_1, a_2, \dots)$ and $\beta = (b_1, b_2, \dots)$, and the product of α by a scalar p are defined as

$$\alpha + \beta \equiv (a_1 + b_1, a_2 + b_2, \dots), \quad p\alpha \equiv \alpha p \equiv (pa_1, pa_2, \dots).$$

The product $\alpha\beta$ we define by the formula

$$\alpha\beta \equiv a_1b_1 + a_2b_2 + \dots$$

whenever this series converges. When α and β have finite norms their product $\alpha\beta$ always exists, as then the series in question is absolutely convergent. For writing

$$\alpha_k = (|a_1|, |a_2|, \dots, |a_k|), \quad \beta_k = (|b_1|, |b_2|, \dots, |b_k|)$$

we have from Theorems 2 and 4

$$G(\alpha_k, \beta_k) = \begin{vmatrix} \alpha_k \bar{\alpha}_k & \alpha_k \bar{\beta}_k \\ \beta_k \bar{\alpha}_k & \beta_k \bar{\beta}_k \end{vmatrix} \geq 0.$$

Hence, as $\alpha_k = \bar{\alpha}_k$ and $\beta_k = \bar{\beta}_k$,

$$(\alpha_k \beta_k)^2 \leq \text{norm } \alpha \cdot \text{norm } \beta$$

or

$$|a_1b_1| + \dots + |a_kb_k| \leq |\alpha| |\beta|.$$

Since this holds for all values of k , the absolute convergence of our series is established.

The distributive law, $\alpha(\beta + \gamma) = \alpha\beta + \alpha\gamma$, evidently holds when $\alpha\beta$ and $\alpha\gamma$ have meanings. Thus, in particular, if α and β have finite norms, we have

$$\text{norm } (\alpha + \beta) = (\alpha + \beta)(\bar{\alpha} + \bar{\beta}) = \alpha\bar{\alpha} + \beta\bar{\alpha} + \alpha\bar{\beta} + \beta\bar{\beta},$$

so that if two complex quantities have finite norms their sum also has a finite norm. It is also obviously true that if a complex quantity has a finite norm it will still have a finite norm after being multiplied by a scalar. From these two facts we readily infer that if a number of complex quantities have finite norms any complex quantity linearly dependent upon them also has a finite norm.

Using the $n + 1$ complex quantities

$$\begin{aligned} \alpha_i &= (a_{i1}, a_{i2}, \dots) & (i = 1, 2, \dots, n), \\ \xi &= (x_1, x_2, \dots), \end{aligned}$$

the equations (14) may be written

$$(15) \quad \alpha_1\xi = 0, \alpha_2\xi = 0, \dots, \alpha_n\xi = 0.$$

We place upon the coefficients α_i the restriction that they have finite norms. Then ξ is to be so determined that the series $\alpha_i\xi$ all converge to the value

zero. If ξ has a finite norm the series $\alpha_i \xi$ necessarily converge, but this may also be the case when ξ has an infinite norm.

THEOREM 7. *If ξ satisfies the equations (15) and is linearly dependent on $\bar{\alpha}_1, \bar{\alpha}_2, \dots, \bar{\alpha}_n$, then $\xi = 0$.*

The proof is exactly that of Theorem 1. We shall define the Gramian of a set of complex quantities of finite norm precisely as was done in § 2.

THEOREM 8. *A necessary and sufficient condition that n complex quantities of finite norm be linearly dependent is that their Gramian vanish.*

The proof is precisely that of Theorem 2.

THEOREM 9. *If equations (15) are linearly independent, their general solution is given by formula (5), where η is any complex quantity such that the products $\alpha_1 \bar{\eta}, \alpha_2 \bar{\eta}, \dots, \alpha_n \bar{\eta}$ all exist.*

The proof is practically identical with that of Theorem 3. In order that the solution ξ_1 have a finite norm it is necessary and sufficient, as we see from (3), that η have a finite norm.

Here, as in § 2, it is clear that two $\bar{\eta}$'s lead to the same solution ξ_1 when and only when their difference is linearly dependent upon $\bar{\alpha}_1, \bar{\alpha}_2, \dots, \bar{\alpha}_n$.

The requirement that η be so chosen that $\alpha_1 \bar{\eta}, \alpha_2 \bar{\eta}, \dots, \alpha_n \bar{\eta}$ all exist will be fulfilled when η has a finite norm. It will, however, be fulfilled in many other cases. For example, denoting the components of α_i by a_{ij} , a_{i2}, \dots , if all the a_{ij} 's are positive and a_{ij} constantly decreases and approaches zero with increasing j , we may take for η the complex quantity $(+1, -1, +1, -1, \dots)$ whose norm is infinite.

Whenever ξ_1 has a finite norm, i. e., whenever this is true of η , its norm is given by formula (7). As in § 2 this formula may be now used to establish

THEOREM 10. *The Gramian of any number of linearly independent complex quantities of finite norm is real and positive.*

We now pass to the non-homogeneous equations:

$$(16) \quad \alpha_1 \xi = b_1, \alpha_2 \xi = b_2, \dots, \alpha_n \xi = b_n,$$

the coefficients α_i again being assumed to have finite norms.

THEOREM 11. *If $\alpha_1, \alpha_2, \dots, \alpha_n$ are linearly independent, the equations (16) have one and only one solution linearly dependent upon $\bar{\alpha}_1, \bar{\alpha}_2, \dots, \bar{\alpha}_n$, and this solution is given by formula (10).*

The proof is precisely that of Theorem 5. The solution in question is termed the *principal solution*. The general solution of (16) is given by formula (11), where $\bar{\eta}$ is any complex quantity whose products with $\alpha_1, \alpha_2, \dots, \alpha_n$ exist.

THEOREM 12. *Among the solutions of (16) no other has so small a norm as the principal solution.*

The principal solution, being a linear combination of $\bar{\alpha}_1, \bar{\alpha}_2, \dots, \bar{\alpha}_n$,

has a finite norm. This is also true of the general solution, $\xi = \xi_0 + \xi_1$, when and only when ξ_1 has a finite norm. From here on the proof is just like that of Theorem 6.

The norm of ξ_0 is given by formula (13).*

5. Some Theorems on the Limits of Complex Quantities. We proceed to establish some properties, which will be important for us, of complex quantities with an infinite number of components.†

If α and β have finite norms, we have from Theorems 8 and 10

$$G(\alpha, \bar{\beta}) = \begin{vmatrix} \alpha\bar{\alpha} & \alpha\bar{\beta} \\ \bar{\beta}\bar{\alpha} & \bar{\beta}\bar{\beta} \end{vmatrix} = |\alpha|^2 |\beta|^2 - |\alpha\beta|^2 \geq 0,$$

whence

$$(17) \quad |\alpha\beta| \leq |\alpha| |\beta|.$$

Again, if $\gamma = \alpha + \beta$, we have, using (17) and remembering that $|\bar{\alpha}| = |\alpha|$,

$$(18) \quad |\gamma|^2 = (\alpha + \beta)(\bar{\alpha} + \bar{\beta}) = \alpha\bar{\alpha} + \alpha\bar{\beta} + \beta\bar{\alpha} + \beta\bar{\beta} \leq |\alpha|^2 + 2|\alpha||\beta| + |\beta|^2,$$

$$(18) \quad |\gamma| \leq |\alpha| + |\beta|.$$

We next lay down the following

DEFINITIONS. If $\alpha_n = (a_{n1}, a_{n2}, \dots)$, $\alpha = (a_1, a_2, \dots)$, we say that α_n converges to α as n becomes infinite when

$$\lim_{n \rightarrow \infty} a_{ni} = a_i \quad (i = 1, 2, \dots),$$

and write

$$\lim_{n \rightarrow \infty} \alpha_n = \alpha.$$

We say that α_n has strong convergence toward α when, for all values of n greater than a certain number, $\alpha - \alpha_n$ has a finite norm, and

$$\lim_{n \rightarrow \infty} |\alpha - \alpha_n| = 0,$$

and write, using Schmidt's notation,

$$\lim_{n \rightarrow \infty} \alpha_n = \alpha.$$

Strong convergence implies convergence. For if $\lim_{n \rightarrow \infty} |\alpha - \alpha_n| = 0$, there exists, for every positive ϵ , an integer N such that

$$(19) \quad \sum_{i=1}^{\infty} |a_i - a_{ni}|^2 < \epsilon^2, \quad n > N,$$

* The theorem regarding bordered Gramians, stated in the footnote to formula (13), may now be generalized so as to apply to the Gramians of complex quantities with finite norms.

† Due to E. Schmidt, l. c., §§ 1-4. See also Kowalewski, l. c., § 165.

so that

$$(20) \quad |a_i - a_{ni}| < \epsilon, \quad \left\{ \begin{array}{l} (i = 1, 2, \dots), \\ n > N, \end{array} \right\}$$

or

$$\lim_{n \rightarrow \infty} a_{ni} = a_i \quad (i = 1, 2, \dots).^*$$

If $\lim_{n \rightarrow \infty} \alpha_n = \alpha$ and α_n has a finite norm when n is greater than a certain number, then α will have a finite norm. For (19) states that when $n > N$, $\alpha - \alpha_n$ has a finite norm; consequently the sum of α_n and $\alpha - \alpha_n$ has a finite norm.

Again, if $\lim_{n \rightarrow \infty} \alpha_n = \alpha$, $\lim_{n \rightarrow \infty} \beta_n = \beta$, then

$$(21) \quad \lim_{n \rightarrow \infty} (\alpha_n + \beta_n) = \alpha + \beta;$$

for we have seen that when $n > N$, $\alpha - \alpha_n$ and $\beta - \beta_n$ have finite norms, and hence from (18) we have

$$|\alpha + \beta - \alpha_n - \beta_n| \leq |\alpha - \alpha_n| + |\beta - \beta_n|.$$

Furthermore if α_n, β_n have finite norms when $n > N$, so that α, β have finite norms,

$$(22) \quad \lim_{n \rightarrow \infty} \alpha_n \beta_n = \alpha \beta;$$

for when $n > N$, we have, using (17) and (18),

$$\begin{aligned} |\alpha \beta - \alpha_n \beta_n| &= |(\alpha - \alpha_n)\beta + (\beta - \beta_n)\alpha - (\alpha - \alpha_n)(\beta - \beta_n)| \\ &\leq |\alpha - \alpha_n| |\beta| + |\beta - \beta_n| |\alpha| + |\alpha - \alpha_n| |\beta - \beta_n|. \end{aligned}$$

Important special cases of (22) are

$$(23) \quad \lim_{n \rightarrow \infty} \alpha_n \beta = \alpha \beta;$$

$$(24) \quad \lim_{n \rightarrow \infty} \text{norm } \alpha_n = \text{norm } \alpha.$$

THEOREM 13. A necessary and sufficient condition that $\lim_{n \rightarrow \infty} \alpha_n$ exist is that, when n and m are any integers greater than a certain number, $\alpha_n - \alpha_m$ have a finite norm, and that to every positive ϵ there correspond an integer N such that

$$(25) \quad |\alpha_n - \alpha_m| < \epsilon, \quad m, n > N.$$

The condition is necessary; for if $\lim_{n \rightarrow \infty} \alpha_n = \alpha$, $|\alpha - \alpha_n| < \frac{1}{2}\epsilon$ when $n > N$. Hence when $m, n > N$

* We say that α_n converges uniformly toward α when for every positive ϵ there exists an N such that (20) is true. It is clear from the above that strong convergence implies uniform convergence, and uniform convergence implies convergence; but these implications do not hold in the reverse order.

$$|\alpha_n - \alpha_m| = |\alpha_n - \alpha + \alpha - \alpha_m| \leq |\alpha_n - \alpha| + |\alpha - \alpha_m| < \epsilon.$$

To show the sufficiency of the condition we first observe that if (25) holds,

$$\sum_{k=1}^n |a_{nk} - a_{mk}|^2 < \epsilon^2, \quad m, n > N,$$

and hence

$$|a_{nk} - a_{mk}| < \epsilon, \quad \left\{ \begin{array}{l} (k = 1, 2, \dots), \\ m, n > N. \end{array} \right\}$$

This shows that $\lim_{n \rightarrow \infty} a_{nk}$ exists; denote it by a_k . Then as

$$\sum_{k=1}^p |a_{nk} - a_{mk}|^2 < \epsilon^2, \quad m, n > N,$$

$$\lim_{n \rightarrow \infty} \sum_{k=1}^p |a_{nk} - a_{mk}|^2 = \sum_{k=1}^p |a_k - a_{mk}|^2 \leq \epsilon^2, \quad m > N.$$

As this holds for every p , we have

$$\sum_{k=1}^{\infty} |a_k - a_{mk}|^2 \leq \epsilon^2, \quad m > N;$$

or, upon writing $\alpha = (a_1, a_2, \dots)$,

$$\lim_{m \rightarrow \infty} |\alpha - \alpha_m| = 0$$

as we wished to prove.

COROLLARY. When condition (25) is fulfilled and α_n is always of finite norm, α is also of finite norm.

DEFINITION. The infinite series of complex quantities $\alpha_1 + \alpha_2 + \dots$ is said to converge strongly to a complex quantity σ when σ_n converges strongly to σ , where $\sigma_n = \alpha_1 + \dots + \alpha_n$.

From Theorem 13 we see that a necessary and sufficient condition for the strong convergence of the above series is that after a certain point the terms of the series all have finite norms and that, to every positive ϵ , there correspond an integer N such that

$$(26). \quad |\sigma_n - \sigma_m| = |\alpha_{m+1} + \alpha_{m+2} + \dots + \alpha_n| < \epsilon, \quad m, n > N.$$

DEFINITION. Two complex quantities α, β , are said to be orthogonal if $\alpha\bar{\beta}$, and hence also $\bar{\alpha}\beta$, is zero.

If the α 's have finite norms and are mutually orthogonal, we may, by squaring (26), readily reduce it to the form

$$|\alpha_{m+1}|^2 + |\alpha_{m+2}|^2 + \dots + |\alpha_n|^2 < \epsilon^2, \quad m, n > N.$$

This being precisely a necessary and sufficient condition that the series $|\alpha_1|^2 + |\alpha_2|^2 + \dots$ converge, we have proved

THEOREM 14. A series of mutually orthogonal complex quantities of

finite norm is strongly convergent when and only when the series of their norms converges.*

Furthermore as $|\sigma_n|^2 = |\alpha_1|^2 + |\alpha_2|^2 + \dots + |\alpha_n|^2$, we infer from (24) the

COROLLARY. If the conditions of Theorem 14 are fulfilled, the norm of the series is equal to the series of the norms of the terms.

6. System of an Infinite Number of Linear Equations in an Infinite Number of Variables. We are now in position to consider the infinite system of homogeneous equations in an infinite number of variables

$$(27) \quad \alpha_1 \xi = 0, \quad \alpha_2 \xi = 0, \quad \dots,$$

where

$$\alpha_i = (a_{i1}, a_{i2}, \dots) \quad (i = 1, 2, \dots),$$

$$\xi = (x_1, x_2, \dots).$$

We assume that all the coefficients α_i have finite norms and none of them are linearly dependent. The general solution, $\xi_1^{(n)}$, of the first n of these equations is given by formula (5)

$$(28) \quad \xi_1^{(n)} = \sum_{i=1}^n c_i^{(n)} \bar{\alpha}_i + \bar{\eta} = \frac{\begin{vmatrix} \alpha_1 \bar{\alpha}_1 & \alpha_1 \bar{\alpha}_2 & \dots & \alpha_1 \bar{\alpha}_n & \alpha_1 \bar{\eta} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \alpha_n \bar{\alpha}_1 & \alpha_n \bar{\alpha}_2 & \dots & \alpha_n \bar{\alpha}_n & \alpha_n \bar{\eta} \end{vmatrix}}{f(\alpha_1, \alpha_2, \dots, \alpha_n)}.$$

Here $(c_1^{(n)}, c_2^{(n)}, \dots, c_n^{(n)})$ is a solution of equations (4).

We wish to show that $\xi_1^{(n)}$ converges strongly to a limit as $n = \infty$; and to this end we proceed to throw it into the form

$$\xi_1^{(n)} = \xi_1^{(1)} + (\xi_1^{(2)} - \xi_1^{(1)}) + \dots + (\xi_1^{(n)} - \xi_1^{(n-1)}).$$

If we write

$$c_i^{(n)} - c_i^{(n-1)} = z_i^{(n)} \quad (i = 1, 2, \dots, n-1),$$

$$c_n^{(n)} = z_n^{(n)},$$

and subtract from the first $n-1$ equations (4) the similar equations satisfied by $(c_1^{(n-1)}, \dots, c_{n-1}^{(n-1)})$, we find that the z 's satisfy the $n-1$ homogeneous equations

$$\begin{cases} \alpha_1 \bar{\alpha}_1 z_1^{(n)} + \alpha_1 \bar{\alpha}_2 z_2^{(n)} + \dots + \alpha_1 \bar{\alpha}_n z_n^{(n)} = 0 \\ \vdots \\ \alpha_{n-1} \bar{\alpha}_1 z_1^{(n)} + \alpha_{n-1} \bar{\alpha}_2 z_2^{(n)} + \dots + \alpha_{n-1} \bar{\alpha}_n z_n^{(n)} = 0. \end{cases}$$

* The proof above establishes the more general theorem in which the condition of orthogonality is replaced by the condition $\alpha_i \bar{\alpha}_j + \alpha_j \bar{\alpha}_i = 0$ or (real part of $\alpha_i \bar{\alpha}_j = 0$ when $i \neq j$, $i, j = 1, 2, \dots$.

Moreover we have

$$\xi_1^{(n)} - \xi_1^{(n-1)} = z_1^{(n)}\bar{\alpha}_1 + z_2^{(n)}\bar{\alpha}_2 + \dots + z_n^{(n)}\bar{\alpha}_n \quad (n = 2, 3, \dots).$$

Solving the homogeneous equations for the z 's and substituting in the last equation, we have

$$(29) \quad \xi_1^{(n)} - \xi_1^{(n-1)} = k_n \varphi_n,$$

where k_n is an undetermined scalar and

$$\varphi_n = \begin{vmatrix} \alpha_1 \bar{\alpha}_1 & \alpha_1 \bar{\alpha}_2 & \dots & \alpha_1 \bar{\alpha}_n \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{n-1} \bar{\alpha}_1 & \alpha_{n-1} \bar{\alpha}_2 & \dots & \alpha_{n-1} \bar{\alpha}_n \\ \bar{\alpha}_1 & \bar{\alpha}_2 & \dots & \bar{\alpha}_n \end{vmatrix} \quad (n = 2, 3, \dots).$$

Multiplying both sides of (29) by α_n and using (28), we find $-H_n/G_{n-1} = k_n G_n$, where, for brevity, we have written

$$H_n = \begin{vmatrix} \alpha_1 \bar{\alpha}_1 & \alpha_1 \bar{\alpha}_2 & \dots & \alpha_1 \bar{\alpha}_{n-1} & \alpha_1 \bar{\eta} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \alpha_{n-1} \bar{\alpha}_1 & \alpha_{n-1} \bar{\alpha}_2 & \dots & \alpha_{n-1} \bar{\alpha}_{n-1} & \alpha_{n-1} \bar{\eta} \\ \alpha_n \bar{\alpha}_1 & \alpha_n \bar{\alpha}_2 & \dots & \alpha_n \bar{\alpha}_{n-1} & \alpha_n \bar{\eta} \end{vmatrix} \quad (n = 2, 3, \dots),$$

$$G_n = G(\alpha_1, \dots, \alpha_n).$$

Therefore

$$\xi_1^{(n)} - \xi_1^{(n-1)} = -\frac{H_n}{G_{n-1}G_n} \varphi_n;$$

and as $\xi_1^{(1)} = \bar{\eta} - (\alpha_1 \bar{\eta}/\alpha_1 \bar{\alpha}_1) \bar{\alpha}_1$, we have, if we set $\varphi_1 = \bar{\alpha}_1$, $G_0 = 1$, $H_1 = \alpha_1 \bar{\eta}$,

$$(30) \quad \xi_1^{(m)} = \bar{\eta} - \sum_{n=1}^{m-1} \frac{H_n}{G_{n-1}G_n} \varphi_n.$$

If η , and hence $\xi_1^{(m)}$, has a finite norm, we see from (6) that $\text{norm } \xi_1^{(m)} = \eta \xi_1^{(m)}$. Assuming, then, that this is the case, we have, since $\varphi_n \eta = \bar{H}_n$,

$$(31) \quad \text{norm } \xi_1^{(m)} = |\eta|^2 - \sum_{n=1}^{m-1} \frac{|H_n|^2}{G_{n-1}G_n}.$$

The series of positive or zero terms

$$(32) \quad \sum_{n=1}^{\infty} \frac{|H_n|^2}{G_{n-1}G_n}$$

is therefore convergent for every η of finite norm since the sum of its first m terms is by (31) not greater than $|\eta|^2$.

We next note that the terms of the series of complex quantities of finite norm

$$(33) \quad \sum_{n=1}^{\infty} \frac{H_n}{G_{n-1}G_n} \varphi_n$$

are mutually orthogonal; for as

$$\varphi_n \alpha_i = 0 \quad (i = 1, 2, \dots, n-1).$$

we have

$$\varphi_n \bar{\varphi}_m = 0, \quad m < n.$$

By Theorem (14) the series (33) will converge strongly if the series of the norms of its terms converges. If we use the relation

$$\varphi_n \bar{\varphi}_n = \varphi_n \alpha_n G_{n-1} = G_n G_{n-1},$$

this series of norms proves to be precisely (32), which we have just shown to be convergent when η is of finite norm. Hence series (33) converges strongly when η has a finite norm, as does likewise the series

$$(34) \quad \xi_1 = \lim_{m \rightarrow \infty} \xi_1^{(m)} = \bar{\eta} - \sum_{n=1}^{\infty} \frac{H_n}{G_{n-1}G_n} \varphi_n = \bar{\eta} - \sum_{n=1}^{\infty} \frac{\bar{\eta} \bar{\varphi}_n}{\varphi_n \bar{\varphi}_n} \varphi_n.$$

ξ_1 is a solution of equations (27) having a finite norm. For consider any one of these equations, say $\alpha_k \xi = 0$: since

$$\alpha_k \xi_1^{(m)} = 0 \quad (m = k, k+1, \dots),$$

we have from (23)

$$\lim_{m \rightarrow \infty} (\alpha_k \xi_1^{(m)}) = \alpha_k \xi_1 = 0.$$

That ξ_1 is of finite norm follows from the fact that $\xi_1^{(m)}$ is always of finite norm and converges *strongly* towards ξ_1 .

Conversely, if ξ_1 is any solution of equations (27), we may obtain it by letting $\bar{\eta} = \xi_1$ in the formula (34), for then all the terms after the first vanish. Thus we have proved

THEOREM 15. *If η is a complex quantity of finite norm, $\xi_1^{(n)}$, given by formula (28), approaches a limiting complex quantity of finite norm as n becomes infinite, and this limit, ξ_1 , is a solution of the equations (27).*

Conversely, every solution of (27), whether of finite norm or not, can be obtained by properly choosing η in (34).

From formulas (24) and (31) we have

$$(35) \quad \text{norm } \xi_1 = \lim_{m \rightarrow \infty} \text{norm } \xi_1^{(m)} = |\eta|^2 - \sum_{n=1}^{\infty} \frac{|H_n|^2}{G_{n-1}G_n}$$

whenever η is of finite norm. Referring to (7), we see that this may also be written as

$$(36) \quad \text{norm } \xi_1 = \lim_{n \rightarrow \infty} \frac{G(\alpha_1, \alpha_2, \dots, \alpha_n, \eta)}{G(\alpha_1, \alpha_2, \dots, \alpha_n)}$$

We turn now to the non-homogeneous equations

$$(37) \quad \alpha_1 \xi = b_1, \quad \alpha_2 \xi = b_2, \quad \dots,$$

where we again assume that all the coefficients α_i have finite norms and none of them are linearly dependent. The principal solution of the first n of these equations, which we will denote by $\xi_0^{(n)}$, is given by formula (10)

$$(38) \quad \xi_0^{(n)} = \sum_{i=1}^n c_i^{(n)} \bar{\alpha}_i = \frac{\begin{vmatrix} \alpha_1 \bar{\alpha}_1 & \alpha_1 \bar{\alpha}_2 & \dots & \alpha_1 \bar{\alpha}_n & -b_1 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \alpha_n \bar{\alpha}_1 & \alpha_n \bar{\alpha}_2 & \dots & \alpha_n \bar{\alpha}_n & -b_n \end{vmatrix}}{\begin{vmatrix} \bar{\alpha}_1 & \bar{\alpha}_2 & \dots & \bar{\alpha}_n & 0 \end{vmatrix}} = \frac{\begin{vmatrix} \alpha_1 \bar{\alpha}_1 & \alpha_1 \bar{\alpha}_2 & \dots & \alpha_1 \bar{\alpha}_n & -b_1 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \alpha_n \bar{\alpha}_1 & \alpha_n \bar{\alpha}_2 & \dots & \alpha_n \bar{\alpha}_n & -b_n \end{vmatrix}}{G(\bar{\alpha}_1, \bar{\alpha}_2, \dots, \bar{\alpha}_n)}$$

Here $(c_1^{(n)}, c_2^{(n)}, \dots, c_n^{(n)})$ is a solution of the equations obtained from (4) by replacing their right-hand members, $-\alpha_1 \bar{\eta}, -\alpha_2 \bar{\eta}, \dots, -\alpha_n \bar{\eta}$ by b_1, b_2, \dots, b_n respectively. A consideration of the process by which $\xi_1^{(n)} - \xi_1^{(n-1)}$ was obtained shows that we may obtain $\xi_0^{(n)} = \xi_0^{(n-1)}$ from this expression by replacing $-\alpha_1 \bar{\eta}, -\alpha_2 \bar{\eta}, \dots, -\alpha_n \bar{\eta}$ by b_1, b_2, \dots, b_n respectively; consequently in place of H_n we must now introduce the determinant

$$B_1 = b_1, \quad B_n = \begin{vmatrix} \alpha_1 \bar{\alpha}_1 & \alpha_1 \bar{\alpha}_2 & \dots & \alpha_1 \bar{\alpha}_{n-1} & b_1 \\ \alpha_2 \bar{\alpha}_1 & \alpha_2 \bar{\alpha}_2 & \dots & \alpha_2 \bar{\alpha}_{n-1} & b_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \alpha_n \bar{\alpha}_1 & \alpha_n \bar{\alpha}_2 & \dots & \alpha_n \bar{\alpha}_{n-1} & b_n \end{vmatrix} \quad (n = 2, 3, \dots)$$

and we obtain

$$\xi_0^{(n)} - \xi_0^{(n-1)} = \frac{B_n}{G_{n-1} G_n} \varphi_n.$$

As

$$\xi_0^{(1)} = \frac{b_1}{\alpha_1 \bar{\alpha}_1} \bar{\alpha}_1,$$

$$(39) \quad \xi_0^{(m)} = \sum_{n=1}^m \frac{B_n}{G_{n-1} G_n} \varphi_n.$$

We are thus led to consider the series

$$(40) \quad \sum_{n=1}^{\infty} \frac{B_n}{G_{n-1} G_n} \varphi_n$$

whose terms are mutually orthogonal complex quantities of finite norm—as we know from the previously established properties of φ_n . By Theorem 14 this series will be strongly convergent when and only when the series of the norms of its terms

$$(41) \quad \sum_{n=1}^{\infty} \frac{|B_n|^2}{G_{n-1}G_n}$$

converges. Thus when series (41) converges we have

$$(42) \quad \xi_0 \equiv \lim_{m \rightarrow \infty} \xi_0^{(m)} = \sum_{n=1}^{\infty} \frac{B_n}{G_{n-1}G_n} \varphi_n$$

and an argument similar to that which follows (34) shows that ξ_0 is a solution of equations (37) having a finite norm. Now if equations (37) have any solution, ξ , of finite norm, then, as $\xi_0^{(m)}$ is the solution of least norm of the first m of these equations,

$$\text{norm } \xi_0^{(m)} \leq \text{norm } \xi;$$

and since norm $\xi_0^{(m)}$ proves to be precisely the sum of the first m terms of (41), the convergence of this series is established. Thus we have proved

THEOREM 16. *A necessary and sufficient condition that equations (37) have a solution of finite norm is that the series (41) converge. When this is the case, $\xi_0^{(n)}$, given by formula (38), approaches strongly a limiting complex quantity of finite norm as n becomes infinite, and this limit, ξ_0 , is a solution of the equations.*

ξ_0 is termed the *principal solution* of (37). We may form the general solution by adding to the particular solution ξ_0 the general solution ξ_1 of equations (27):

$$(43) \quad \xi = \xi_0 + \xi_1 = \lim_{n \rightarrow \infty} \frac{\begin{vmatrix} \alpha_1 \bar{\alpha}_1 & \alpha_1 \bar{\alpha}_2 & \cdots & \alpha_1 \bar{\alpha}_n & \alpha_1 \bar{\eta} - b_1 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \alpha_n \bar{\alpha}_1 & \alpha_n \bar{\alpha}_2 & \cdots & \alpha_n \bar{\alpha}_n & \alpha_n \bar{\eta} - b_n \\ \bar{\alpha}_1 & \bar{\alpha}_2 & \cdots & \bar{\alpha}_n & \bar{\eta} \end{vmatrix}}{G(\alpha_1, \alpha_2, \dots, \alpha_n)}$$

From the Corollary to Theorem 14 we have

$$\text{norm } \xi_0 = \sum_{n=1}^{\infty} \frac{|B_n|^2}{G_{n-1}G_n},$$

or, referring to (13),

$$(44) \quad \text{norm } \xi_0 = \lim_{n \rightarrow \infty} - \frac{\begin{vmatrix} \alpha_1 \bar{\alpha}_1 & \alpha_1 \bar{\alpha}_2 & \cdots & \alpha_1 \bar{\alpha}_n & b_1 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \alpha_n \bar{\alpha}_1 & \alpha_n \bar{\alpha}_2 & \cdots & \alpha_n \bar{\alpha}_n & b_n \\ \bar{b}_1 & \bar{b}_2 & \cdots & \bar{b}_n & 0 \end{vmatrix}}{G(\alpha_1, \alpha_2, \dots, \alpha_n)}$$

If ξ_1 has a finite norm, the same is true of ξ , and

$$\text{norm } \xi = \text{norm } \xi_0 + \text{norm } \xi_1,$$

for from (38) $\xi_0^{(n)} \bar{\xi}_1 = 0$, so that upon applying (23), $\xi_0 \bar{\xi}_1 = \xi_1 \bar{\xi}_0 = 0$. Consequently

$$\text{norm } \xi \geq \text{norm } \xi_0$$

the sign of equality holding only when $\xi_1 = 0$, in which case $\xi = \xi_0$. Thus we have proved

THEOREM 17. *Among the solutions of (37) no other has so small a norm as the principal solution.*

7. Some further facts.—The general solution ξ_1 of the homogeneous equations (27) is a function of the complex parameter η

$$\xi_1 = \psi(\eta).$$

A glance at (28) shows us at once that ψ is, in an extended sense, a linear function; that is

THEOREM 18. *If $\eta', \eta'', \dots, \eta^{(k)}$ are complex quantities with finite norms and c_1, \dots, c_k are scalars, then*

$$\psi(c_1 \eta' + \dots + c_k \eta^{(k)}) = c_1 \psi(\eta') + \dots + c_k \psi(\eta^{(k)}).$$

A further important fact is that ψ has strong continuity for every value of η with finite norm; that is

THEOREM 19. *If η' has a finite norm, then as η approaches η' strongly, $\psi(\eta)$ approaches $\psi(\eta')$ strongly.*

To prove this, we derive from Theorem 18 and from (35) the relation

$$\text{norm } [\psi(\eta') - \psi(\eta)] = \text{norm } \psi(\eta' - \eta) \leq \text{norm } (\eta' - \eta),$$

from which our theorem follows at once.

Let us now denote the components of η by y_1, y_2, \dots , and the complex quantity whose first n components are y_1, \dots, y_n while all its subsequent components are zero by η_n . Then, if η is of finite norm,

$$(45) \quad \lim_{n \rightarrow \infty} \eta_n = \eta.$$

For $\text{norm } (\eta - \eta_n) = |y_{n+1}|^2 + |y_{n+2}|^2 + \dots$, and, this being the remainder of a convergent series, approaches zero as n becomes infinite.

Let us denote by ϵ_i the complex quantity whose i th component is 1 while all its other components are zero. Then

$$\psi(\epsilon_i) = \lim_{n \rightarrow \infty} \frac{\begin{vmatrix} \alpha_1 \bar{\alpha}_1 & \dots & \alpha_1 \bar{\alpha}_n & \alpha_{1i} \\ \dots & \dots & \dots & \dots \\ \alpha_n \bar{\alpha}_1 & \dots & \alpha_n \bar{\alpha}_n & \alpha_{ni} \\ \bar{\alpha}_1 & \dots & \bar{\alpha}_n & \epsilon_i \end{vmatrix}}{G(\alpha_1, \dots, \alpha_n)}.$$

THEOREM 20. *A necessary and sufficient condition that the homogeneous system (27) have no solution of finite norm except zero is that all the quantities $\psi(\epsilon_i)$ be zero.*

That this is a necessary condition is obvious. To prove it sufficient assume $\psi(\epsilon_i) = 0$ ($i = 1, 2, \dots$). By Theorem 18, $\psi(\eta) = 0$ whenever η has only a finite number of components different from zero. But, by (45), every η of finite norm is the strong limit of such a set of η 's. Consequently, by Theorem 19, $\psi(\eta) = 0$ for every η of finite norm, as was to be proved.

We have expressed the solutions ξ_1 and ξ_0 as well as their norms, as the limit of the ratio of two determinants of order $n+1$ and n as n becomes infinite. We proceed to inquire under what conditions the individual determinants, and not merely their ratios, converge. In all cases the denominator determinant is $G(\alpha_1, \dots, \alpha_n)$, and if this Gramian converges as n becomes infinite, the determinants in the numerators will likewise converge. Thus we have merely to consider the convergence of $G(\alpha_1, \dots, \alpha_n)$ as n becomes infinite, or, as we phrase it, the convergence of the infinite Gramian, $G(\alpha_1, \alpha_2, \dots)$.

THEOREM 21. *A sufficient condition for the convergence of the infinite Gramian of the complex quantities $\alpha_1, \alpha_2, \dots$ which have finite norms is that the infinite product $\prod_{i=1}^{\infty} |\alpha_i|^2$ diverge to zero or converge.*

Consider the set of complex quantities $\beta_i = \alpha_i/|\alpha_i|$ whose norms are all unity. We have, then,

$$(46) \quad G(\alpha_1, \dots, \alpha_n) = G(\beta_1, \dots, \beta_n) \prod_{i=1}^n |\alpha_i|^2.$$

Now

$$G(\beta_1, \dots, \beta_n) = \begin{vmatrix} \beta_1 \bar{\beta}_1 & \dots & \beta_1 \bar{\beta}_{n-1} & \beta_1 \bar{\beta}_n \\ \vdots & \ddots & \vdots & \vdots \\ \beta_{n-1} \bar{\beta}_1 & \dots & \beta_{n-1} \bar{\beta}_{n-1} & \beta_{n-1} \bar{\beta}_n \\ \beta_n \bar{\beta}_1 & \dots & \beta_n \bar{\beta}_{n-1} & 0 \end{vmatrix} + |\beta_n|^2 G(\beta_1, \dots, \beta_{n-1}).$$

The first term on the right is a bordered Gramian of the form of the numerator of (13) and is therefore negative or zero (see footnote at the end of § 3). Consequently

$$G(\beta_1, \dots, \beta_n) \leq G(\beta_1, \dots, \beta_{n-1});$$

and since $G(\beta_1, \dots, \beta_n)$ is never negative, $\lim_{n \rightarrow \infty} G(\beta_1, \dots, \beta_n)$ exists. Thus when $\prod_{i=1}^{\infty} |\alpha_i|^2$ diverges to zero or converges, we have from (46) that $G(\alpha_1, \alpha_2, \dots)$ converges, as we wished to prove.

COROLLARY 1. *If $G(\beta_1, \beta_2, \dots) \neq 0$ the condition that $\prod_{i=1}^{\infty} |\alpha_i|^2$ diverge to zero or converge is also necessary for the convergence of $G(\alpha_1, \alpha_2, \dots)$.*

COROLLARY 2. *If $\prod_{i=1}^{\infty} |\alpha_i|^2 = 0$, then $G(\alpha_1, \alpha_2, \dots) = 0$.*

We also note that $G(\alpha_1, \alpha_2, \dots) = 0$ when any of the complex quantities α_i are linearly dependent.

From Theorem 21 we now see that the determinants occurring in the expressions for $\xi_1^{(n)}$ and $\xi_0^{(n)}$ (and for their norms) will converge as $n = \infty$ if, at the start, the equations (27) and (37) respectively are divided through by scalars so as to make the norms of all the α 's ≤ 1 . If, when this is done, $G(\alpha_1, \alpha_2, \dots) \neq 0$, the formulæ for ξ_1 and ξ_0 furnish solutions for these infinite systems of equations in terms of infinite determinants, properly so called. Of course the last row and column of the numerator determinants must then be written as first row and column.

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APPENDIX III

Consider an infinite dimensional vector space $V \{ \xi, \eta, \zeta, \dots \}$ over the field of complex numbers. Each vector is of the form

$$\xi = (x_1, x_2, \dots, x_n, \dots) , \quad (1)$$

or

$$\xi = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ \vdots \\ x_n \\ \vdots \\ \vdots \end{pmatrix} \quad (2)$$

where the components x_i are from the complex field. Place the restriction on the vectors of V that

$$\sum_{i=1}^{\infty} |x_i|^2 \text{ converges.} \quad (3)$$

Define the inner product of two vectors as

$$(\xi, \eta) = \sum_{i=1}^{\infty} x_i y_i , \quad (4)$$

where x_i are the components of ξ , and y_i those of η . The series defining the inner product of any two vectors in V converges because of the condition expressed by (3).

Also, define the inner product of a vector with its complex conjugate by

$$(\xi, \bar{\xi}) = ||\xi||^2 = \sum_{i=1}^{\infty} x_i \bar{x}_i = \sum_{i=1}^{\infty} |x_i|^2 \quad (5)$$

Notice that $||\xi|| = 0$ if and only if all the components of ξ are zero. ξ is normal if $||\xi|| = 1$. ξ is orthogonal to η if

$$(\xi, \eta) = 0. \quad (6)$$

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It is obvious that if $\xi_1, \xi_2, \dots, \xi_n$ satisfy condition (3), then

$\alpha_1 \xi_1 + \alpha_2 \xi_2 + \dots + \alpha_n \xi_n$ does.

We say that the sequence $\xi_1, \xi_2, \dots, \xi_n, \dots$ converges strongly to ξ if

$$\lim_{n \rightarrow \infty} \|\xi - \xi_n\| = 0. \quad (7)$$

If we designate by M a set of vectors satisfying condition (3), a vector ξ is a limit vector of M if an η exists in M for every $\epsilon > 0$ such that $\|\xi - \eta\| < \epsilon$. When M contains its limit vectors it is called complete. A complete set M is called linear if, for ξ and η in M , we have all vectors $\alpha_1 \xi + \alpha_2 \eta$ in M .

Let $\xi_\nu, \nu = 1, 2, 3, \dots$ be an infinite set of vectors. If M is the set of all finite linear combinations of the ξ_ν with constant coefficients, then the set $\gamma = M \cup M'$, where M' is the set of limit vectors of M , is a complete linear set, and $\xi_\nu, \nu = 1, 2, 3, \dots$ is a basis for γ . A vector is said to be orthogonal to a set γ if it is orthogonal to its basis. As in the finite case, a basis may be replaced by a normal orthogonal basis. (The so-called Schmidt process).

If γ is a linear set with basis $\xi_\nu, \nu = 1, 2, 3, \dots$; and η is an arbitrary vector satisfying condition (3), then η decomposes in one and only one way into the sum of a vector in γ and a vector orthogonal to γ . That is,

$$\eta = \xi + \rho, \quad (8)$$

where ξ is in γ and ρ is orthogonal to γ . ρ is called the perpendicular vector of η with respect to γ . $\|\rho\| = 0$ if and only if η belongs to γ .

Given a set $\gamma = \{\xi_1, \dots, \xi_n\}$ and $\eta = (y_1, y_2, \dots, y_k, \dots)$, $\xi_i = (x_{i1}, x_{i2}, x_{i3}, \dots, x_{ik}, \dots)$, ρ may be constructed. $\rho = (r_1, r_2, \dots, r_n)$ and let $\mu_{ij} = (\xi_i, \xi_j)$. Then ρ is given by

$$\rho = \begin{vmatrix} \mu_{11} & \mu_{12} & \dots & \dots & \dots & \mu_{1n} & \xi_1 \\ \mu_{21} & \mu_{22} & \dots & \dots & \dots & \mu_{2n} & \xi_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ \mu_{n1} & \mu_{n2} & \dots & \dots & \dots & \mu_{nn} & \xi_n \\ (\xi_1, \eta) & (\xi_2, \eta) & \dots & \dots & \dots & (\xi_n, \eta) & \eta \end{vmatrix} \div \begin{vmatrix} \mu_{11} & \mu_{12} & \dots & \dots & \dots & \mu_{1n} \\ \mu_{21} & \mu_{22} & \dots & \dots & \dots & \mu_{2n} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ \mu_{n1} & \mu_{n2} & \dots & \dots & \dots & \mu_{nn} \end{vmatrix} \quad (9)$$

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If γ possesses an infinite basis ξ_ν , $\nu = 1, 2, \dots$

$$\rho = \eta - \sum_{\nu=1}^{\infty} (\eta, \bar{\beta}_\nu) \beta_\nu, \quad (10)$$

where β_ν is a normal orthogonal basis replacing ξ_ν .

These preliminary concepts will now be applied to the solution of an infinite system of linear equations. Let the given system be

$$\sum_{j=1}^{\infty} a_{ij} x_j = c_i, \quad i = 1, 2, \dots, \quad (11)$$

in matrix solution

$$AX = C. \quad (12)$$

Let α_n represent the vector formed by the complex conjugate of elements in the n^{th} row of the matrix A .

$$\alpha_n = (\bar{a}_{n1}, \bar{a}_{n2}, \dots, \bar{a}_{nn}, \dots) \quad (13)$$

Denote by γ the set with basis $\{\alpha_1, \alpha_2, \dots, \alpha_n, \dots\}$ and denote by γ_n the set with basis $\{\alpha_1, \alpha_2, \dots, \alpha_{n-1}, \alpha_{n+1}, \dots\}$. The set γ_n is the same as γ with α_n removed. Let ρ_n be the perpendicular vector of α_n with respect to γ_n .

THEOREM: If α_n lies in γ_n for no value of n (linear independence of rows), and if $\alpha_1, \alpha_2, \dots, \alpha_n, \dots$ satisfy (3), the eqs. (11) have a solution if

$$\sum_{n=1}^{\infty} \frac{|c_n|^2}{\|\rho_n\|^2}$$

converges, and the solution is given by

$$x_n = \frac{(\rho_n, C)}{\|\rho_n\|^2} \quad (14)$$

In matrix notation the ρ_n , where

$$\rho_n = (r_{n1}, r_{n2}, \dots, r_{nn}, \dots), \quad (15)$$

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form a matrix

$$\begin{pmatrix} \rho_1 \\ \rho_2 \\ \vdots \\ \rho_n \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{pmatrix} \quad (16)$$

If we consider a matrix B , where

$$B = \begin{pmatrix} \frac{r_{11}}{||\rho_1||^2} & \frac{r_{12}}{||\rho_1||^2} & \cdots & \frac{r_{1n}}{||\rho_1||^2} \\ \frac{r_{21}}{||\rho_2||^2} & \frac{r_{22}}{||\rho_2||^2} & \cdots & \frac{r_{2n}}{||\rho_2||^2} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{r_{n1}}{||\rho_n||^2} & \frac{r_{n2}}{||\rho_n||^2} & \cdots & \frac{r_{nn}}{||\rho_n||^2} \end{pmatrix} T \quad (17)$$

and T denotes the transpose operation, then we can write

$$X = BC, \quad (18)$$

where B serves as a left inverse for the matrix A in (12).

F. BIBLIOGRAPHY

1. C. MacDuffee, *The Theory of Matrices*; (1946).
2. *Annals of Mathematics*, Vol. 13, Second Series; 1911-1912.

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3. Riesz, *Les Systems d'Equations Lineaires*; (1913)...

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Investigator *Edward R. Fadell* Date *7/2/51*
Investigator *J. E. Adney Jr.* Date *7/11/51*
Investigator *Edward M. Kennedy* Date *7/11/51*
Investigator *Edward M. Kennedy* Date
Investigator Date
Supervisor *W. A. Rumsby* Date *13 July 51*

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Executive Director *James S. Owens* Date *18 July 1951*
W. E. H.

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